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Published in:
Energies

Link to article, DOI:
10.3390/en6084170

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Energies **2013**, *6*, 4170-4186; doi:10.3390/en6084170

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Energy Analysis of the Danish Food Production System: Food-EROI and Fossil Fuel Dependency

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Received: 29 May 2013; in revised form: 18 July 2013 / Accepted: 18 July 2013 / Published: 15 August 2013

Abstract: Modern food production depends on limited natural resources for providing energy and fertilisers. We assess the fossil fuel dependency for the Danish food production system by means of Food Energy Returned on fossil Energy Invested (Food-EROI) and by the use of energy intensive nutrients from imported livestock feed and commercial fertilisers. The analysis shows that the system requires 221 PJ of fossil energy per year and that for each joule of fossil energy invested in farming, processing and transportation, 0.25 J of food energy is produced; 0.28 when crediting for produced bioenergy. Furthermore, nutrients in commercial fertiliser and imported feed account for 84%, 90% and 90% of total supply of N, P and K, respectively. We conclude that the system is unsustainable because it is embedded in a highly fossil fuel dependent system based on a non-circular flow of nutrients. As energy and thus nutrient constraints may develop in the coming decades, the current system may need to adapt by reducing use of fossil energy at the farm and for transportation of food and feed. An operational strategy may be to relocalise the supply of energy, nutrients, feed and food.

Keywords: Peak Oil; fertiliser; food-EROI; energy analysis; agriculture; food; feed; transport; bioenergy

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1. Introduction

Food is the most basic requirement of any society and having sufficient food is a prerequisite for maintaining social stability. The most important source of food is terrestrial ecosystems, which supplies more than 99% of global food production [1]. By 2030, the world is expected to require at least 50% more food and 45% more energy to sustain the global population growing in numbers and affluence [2]. Understanding the interactions between food and energy supply and demand is, therefore, important for planning of a future sustainable development for agriculture.

Industrialisation of agriculture made it possible to increase food production at roughly the same pace as demand and thus helped the human population to increase by more than 400% in the 20th century. However, since the mid-1980s, the availability of cereal grains (accounting for 80% of the worlds food supply) *per capita* has been decreasing thus indicating that demand is growing faster than supply [3]. The industrialisation of agriculture was a transition from an agricultural practice that mainly relied on flow-limited resources to a practice that increasingly relied on stock-limited resources [4]. A flow-limited resource is plentiful in stock but only available a little at a time, whereas a stock-limited resource has a finite stock which can be used at high pace. In effect, local, flow-limited energy sources like sun and wind and local nutrients such as soil-bound phosphorus and nitrogen from microbial fixation were subsidised by the stock-limited resources of fossil energy, synthesised nitrogen based on natural gas and mineral phosphorus.

Globalisation has fundamentally changed material and energy flows of food production [5]. In high-income countries, the global economy has resulted in specialisation, large-scale production and high labour efficiency made possible by the use of fossil energy and the emergence of complex industrial systems. However, the global economy has come with spatial separation of production and consumption of nutrients for crop production, of feed for livestock production, and of food for human consumption, resulting in non-circular nutrient flows.

Nitrogen (N) is the most common yield-limiting nutrient [6] and much effort has been put into how to manage the crop to prevent yield loss [7]. The discoveries in the early 20th century of how to synthesise ammonia from atmospheric N_2 (by Habor) and how to produce N on a large-scale (by Bosch) have fundamentally changed the global N-cycle: From 1950 to 2000 the global consumption of N fertiliser increased from roughly 4 to more than 85 million ton per year [8]. More than one additional planet of natural N-fixation would be needed to replace the natural gas based N production, and it has been estimated that synthesised N keeps from 44% to 48% of the global population alive [6].

Phosphorus fertiliser (P) is predicted to become increasingly scarce. Unlike the volatile N, P rarely occurs in gaseous forms, and therefore it is ultimately washed out of the continents and accumulates in aquatic sediments. In geological times, these deposits have been made available to terrestrial ecosystems with the grand geotectonic-uplift leading to the formation of mountains and volcanoes [9]. Currently, global P production comes from only a handful of countries and research has suggested that the mining rate of P might peak around 2030 [10,11]. In theory, P can always be recovered, for instance by mining it from the seabed, as P is not used or lost, but moved and diluted. However, the more diluted it becomes, the more energy will be required to recover it, and in a foreseeable future with fossil energy constraints this seems out of reach. In addition to N and P commercial fertiliser usually also includes potash (K); another essential nutrient. However, K is not expected to cause supply limit concerns as the deposits are large and K is primarily incorporated in crop residues and as such not removed from the ecosystem to the same extent [12].

Fossil energy and specifically refined oil plays a key role in directly powering agricultural machinery and the transport system that connects local production to the global market. Further, fossil energy is used to produce commercial fertilisers and machinery needed to produce and process the food. Fossil oil is a limited resource and consequently, at some point in time, oil production will go into a terminal decline [13].

Future energy and nutrient constraints may be among the most important limiting factors and thus among the most important drivers for development of the food production system. Therefore, as also noted by Arizpe *et al.* [14], it is essential to focus on the use of fossil fuels in the food production system when dealing with the issue of food security. Energy analysis is a method for accounting direct and indirect usage of energy to produce a product or service [15]. Following the oil crisis of the 1970s, where it became apparent that fossil fuel depending systems are vulnerable, a rich number of energy analyses of agricultural and food production systems was published, e.g., reviewed in [5]. The results from such analyses may be expressed as food energy returned on direct and indirect fossil energy invested (Food-EROI). Food-EROI values differ very much between studies due to differences in system boundaries, e.g., it is extremely difficult to establish rigorous geographic boundaries around food systems due to global trading. On the Swedish island of Gotland, 1.2 units of food energy were returned at the farmers gate per unit of fossil energy invested in 1972 [16]. A Danish study reported that the Danish output of food energy per input energy decreased from 3.9 to 1.0 over the years from 1936 to 1990 [17]. Recently, it was found that US crop and livestock production has improved the Food-EROI (denoted Edible Energy Efficiency by the authors) from 0.8 in 1970 to 2.3 by 2009 and that Canada in the same period had a steady Food-EROI of around 2 [18]. Fewer studies have expanded the system boundaries to also include transportation and processing of food. One of these is Heller and Keoleian, who analysed the entire US food production system and even included energy use in the homes for storing and preparing food [19].

The objective of this paper is to expand the Danish study from 1994 [17] to include also the food manufacturing industry, energy use for transportation of food and feed and indirect energy used for producing imported feed using data from 2004 to 2007. In this way we also evaluate whether the decrease in Food-EROI observed by Schroll [17] has continued. In addition to the energy analysis, special attention is paid to the nutrient supply, because it at the same time is essential to current production methods and heavily depending on fossil fuel for its supply. In the nutrient flow analysis we quantify the supply of N, P and K to the Danish food production system from external sources; *i.e.*, sources that contribute to replenishing the stock of nutrients in the Danish food production system.

2. Material and Method

This study was based on collating published data into a new context. Unless otherwise is explicitly stated, all inputs and outputs were based on average values for 2004–2007 from Statistics Denmark [20].

2.1. System Boundaries

The Danish food production system was analysed as consisting of three compartments: (1) Danish agriculture and horticulture on the entire Danish arable land (2,668,000 ha) and total Danish livestock production; (2) Danish food manufacturing industry classified according to Statistics Denmark [20]: Production of meat and meat products; Manufacture of dairy products; Manufacture of grain mill and bakery products; Other manufacture of food products (not fishery); and Manufacture of beverages; (3) Transportation of food and agricultural products in Denmark and to and from Denmark. This implies that the analysis consider all material and energy inputs to production and processing of food in Denmark as well as the transport of inputs, intermediate products and food. For food sold in Denmark, the transport analysis ends at the retailer. For exported food, only the first transport distance (typically to large scale distribution centres) is included. In addition, production of bioenergy measured in heating value was included as a negative input based on the assumption that bioenergy replaces fossil fuel in the economy.

For the nutrient flow analysis the system boundaries were also drawn around the Danish Food production system. Flows of nutrients that contribute with replenishment of the stock of nutrients in the sector were considered, *i.e.*, N-fixation by legumes, atmospheric deposits, nutrients in imported feed, commercial fertiliser and waste. The flows of nutrients within the Danish food production system such as nutrients cycling through manure and waste products from the food manufacturing industry were not considered as these flows do not contribute in replenishing the nutrient stock. The nutrient flow analysis was based on an extensive study of the annual nutrient balance during the last century for Danish agriculture [21], which we have summarised in a way reflecting our system boundaries.

2.2. Direct and Indirect Fossil Energy Use and Food-EROI

In energy analysis (sometimes called embodied energy or gross energy requirement) the objective is to quantify the fossil energy required directly and indirectly to allow a system to produce a given output [22]. The direct and indirect fossil energy use (hereafter denoted "Energy Use") was calculated by multiplying input of energy and materials to the studied system with appropriate energy intensities. Energy intensities measure the accumulated fossil energy used to provide one unit of product and are accordingly expressed as energy units per unit of product. The energy intensity of fossil fuel is equal to the sum of its heating value plus the fossil energy used to make the fuel available to the system (*i.e.*, in extraction, refining and transportation). The energy intensities of other resources are accounted for based on the amount of fossil fuel used to make them available to the system. Renewable resources that do not require fossil energy to make them useful to the economy, e.g. solar radiation, wind and rain, as well as labour was not accounted for.

Energy Use was calculated for each of the three compartments identified in Section 2.1 and subsequently aggregated. Food-EROI was calculated as the ratio of the output of food measured in food energy (nutritional value) to Energy Use for the Danish food production system.

2.2.1. Calculation of Energy Use

The Energy Use for Danish agriculture was calculated based on the following inputs: electricity and fuels in joules; commercial fertilisers in tonnes of N, P and K; pesticides in tonnes of active ingredients and imported feed in tonnes of crude protein. We account imported feed in crude protein according to the national statistics. Energy intensities for fuels, electricity, commercial fertiliser and pesticides were based on the JEC E3-database (version 31-7-2008) [23]. The energy intensity for imported crude protein was estimated based on soy beans with an energy intensity of 6.999 GJ per ton including shipping to Netherlands [24] and a 30% protein content [25]. Energy Use for production and maintenance of machinery and buildings in Danish agriculture was based on a previous published estimate of 10 PJ [26]. Domestic produced feed, seed and straw was not included as inputs to avoid double counting.

Energy Use for the transportation of food and agricultural products was calculated based on the transport of goods by road measured in tonne-kilometre (tkm) of the following categories according to Statistics Denmark [20]: foodstuff, animal fodder, sugar beets, potatoes, vegetables, fruits, cereals, fertilisers, live animals, animals and vegetable fats and oils. Transport to Denmark (*i.e.*, import) of other categories than animal feed and fertilisers was excluded to avoid counting transport of food coming from other food systems. However, domestic transport of imported food could not be separated from domestic transport of Danish food. We assumed that this overestimation is counterbalanced by the underestimation of transport of food and agricultural products exported from Denmark. The latter accounts only for the first transport distance out of Denmark, and not the total transport needed to make Danish food products available to foreign consumers at retailers. Regarding transport to and from Denmark by foreign registered trucks, data were only available on an aggregated level including all types of goods (*i.e.*, also those not related to agriculture). It was assumed that the foreign trucks' share of transport of agricultural products was equal to the foreign trucks' share of total Danish transport.

The energy intensity per tkm of transportation was assumed to be 6.5 MJ of fossil energy [27]. This energy intensity was specifically calculated for Denmark based on the total energy use in the road goods transport sector in 2007. Other studies have shown significantly lower energy intensities ranging from 1 MJ/tkm [23] to 1.7 MJ/tkm in Australia and 4.3 MJ/tkm in Japan [28]. The large variability may be explained partly by different system boundaries in the studies and by differences in spatial distribution and landscape. This large variation indicates a high level of uncertainty of the Energy Use for transport. Energy Use for Danish food manufacturing industry was calculated based on the sector's use of energy carriers according to national statistics [20]. For practical reasons, Energy Use for production and maintenance of buildings and machinery was not included for this sector.

2.2.2. Output from the Food Production System

The amount of food energy available to the consumer at the retailer was calculated based on farm-gate output (described below). As a consequence, any food losses from the farm-gate to the consumer were not taken into account.

Danish statistical data regarding production of meat (pig, beef, veal, chicken; minor animal products such as meat from horse, sheep or game were not included), milk, eggs, grain, sugar and vegetables, were converted from mass to food energy as described below.

Animals slaughtered in Denmark and animals exported alive were included. Statistical data in slaughtered weight (carcass including meat and bone) were converted to food energy based on the content of bone-free meat and its food energy value. The content of bone-free meat per kg slaughtered weight was set to 0.59 kg for pigs [29], 0.70 kg for beef and veal [30] and 0.70 kg for chicken (our assumption). The food energy content per kg bone-free meat was 7.54 MJ, 6.96 MJ, 7.66 MJ for pig, beef/veal and chicken, respectively [31].

The production of food based on milk included all milk delivered to dairies and this amount was converted to food energy based on 2.55 MJ/kg [31]. The production of food based on eggs included all eggs delivered to packing stations as well as an official estimate of those sold directly to consumers and this amount was converted to food energy based on 6.52 MJ/kg [31].

The main crops for human consumption were cereals, sugar beets and potatoes, and they were converted to food energy based on 14.73 MJ/kg, 16.98 MJ/kg and 3.55 MJ/kg, respectively [31]. The category "cereals" included cereals used for export, for grinding into flour and groats, and for "other manufacturing purposes". Food products from sugar beets were estimated based on the Danish production of sugar. Food products from potatoes were estimated based on potatoes sold for human consumption, potato flour factories or export. The 13 most commonly produced vegetables and fruits were quantified and each of these was converted to food energy [32].

3. Results and Discussion

In this study, the dependency of fossil fuel for the Danish food production system is analysed based on statistical data. First the results for nutrient flows are examined and subsequently the Energy Use and Food-EROI results are discussed.

3.1. External Supply of N, P and K

On a yearly basis, Danish agriculture was supplied with 446,000 t N (the equivalent of 167 kg per ha agricultural land), of which only 13% came from fossil fuel independent domestic sources (atmospheric deposits and fixation by legumes), 44% came from commercial fertiliser and 40% came from imported feed (Table 1). Likewise the yearly supply of P was 14,000 t (23 kg per ha), of which 67% came from imported feed and 23% from commercial fertilisers. For K, 61,000 t (47 kg per ha) was added, with 49% coming from commercial fertiliser and 41% from imported feed.

As can be seen, replenishment of the stock of N, P and K in Danish agriculture was highly depending on commercial fertilisers and imported feed and thus on fossil energy. Together, these two sources accounted for 84%, 90% and 90% of the total amount of N, P and K supplied to Danish agriculture, respectively. The imported feed supplies protein for animals and the embodied nutrients contribute with fertiliser for crop production. The consequence was a non-circular flow of nutrient protein from exporting countries in mainly South America to Denmark where the nutrients contribute to eutrophication of Danish water systems or are exported to meat importing countries around the world. Such a flow of nutrients can only be sustained for as long as the nutrient stock in the donor country is maintained. As also concluded in a study of Brazilian soy bean export, the issue of nutrient depletion is a complex problem that cannot be solved with present approach of increasing application of chemical fertilisers but must be addressed with holistic agro-ecological methods [33].

Table 1. Supply of nutrients to Danish agriculture (average 2004–2006) based on Kyllingsbæk [21].

Nutrient sources	N		P		K	
	(1000 t)	(%)	(1000 t)	(%)	(1000 t)	(%)
Commercial fertilisers	197	44	14	23	61	49
Imported feed	179	40	40	67	52	41
Waste	12	3	6	10	5	4
Atmospheric deposits	22	5	0	0	8	6
Fixation by legumes	37	8	-	-	-	-
Total	446	100	61	100	125	100

3.2. Energy Use

Energy Use for Danish agriculture (including horticulture) was calculated to be 121 PJ (Table 2) equivalent to 45 GJ per ha of agricultural land. The inputs which contributed the most to Energy Use were electricity (31%), fuels (28%) (oil products; 24%, coal; 2%, and natural gas; 2%) and imported feed (23%). The use of oil products (motor fuel, oil used for heating, petroleum and fuel oil) was calculated to be 29 PJ (corresponding to 258 l/ha of agricultural land). The import of crude protein, of which 67% was in soya cake, is equivalent to increasing the crop production per ha of total agricultural land with more than 450 kg protein. This implies that the imported crude proteins contribute with 43% of total protein used for feed [20]. The direct input of energy carriers (oil products, coal, natural gas and electricity) was 43 PJ representing 35% of the Energy Use (121 PJ) needed to operate the sector (Table 2). The remaining 65% of fossil energy supporting Danish agriculture was used upstream to provide the inputs.

The requirement of 121 PJ of fossil fuel is significantly larger than a recent estimate of 65 PJ [34]. Their energy balance is only a small part of their study and it is therefore not detailed described. Their Energy Use seems to include only the direct use of electricity and not the fossil fuel used to produce the electricity, to omit the horticultural production, and to assume an indirect energy used for imported feed to be 19 instead of 28 in our study due to differences in calculation methods.

Our distribution of Energy Use is in agreement with a study of the US agricultural sector [18], which found that electricity and fuels together accounted for 57%–66% (our calculation based on Table 1 in Hamilton *et al.* [18]), compared to our 59 % (31% + 24% + 2% + 2%, Table 2). They also found machinery to account for 7%–8% which compares directly to our 8%. However, unlike this study, they included seed production and research and development. We excluded seed production to avoid double counting since most seed used by Danish agriculture is also produced by Danish agriculture. An interesting difference between the two studies is that they do not consider imported feed, which may be explained by that US, unlike Denmark, has a high domestic production of protein feed. The high share of nutrients embodied in the imported protein feed (Table 1) in Denmark at least partially explains the lower contribution from commercial fertilisers in our study, 8%, compared to 29%–38% in USA. Another reason may be that fertiliser application is more strictly regulated in Denmark.

Table 2. Annual input to Danish agriculture and corresponding direct and indirect fossil energy use.

Inputs	Unit	Input (unit) [a]	Energy intensity (TJ unit^{-1})	Energy use (PJ)	Energy use (%)
Oil products	TJ	24,637	1.16 [b]	29	24
Coal	TJ	1,877	1.16 [b]	2	2
Natural gas	TJ	2,450	1.13 [b]	3	2
Electricity	TJ	13,964	2.70 [b]	38	31
N-fertiliser	kt	203.3	48.99 [b]	10	8
P-fertiliser	kt	14.1	15.23 [b]	0	0
K-fertiliser	kt	60.4	9.68 [b]	1	1
Pesticides (active ingredients)	kt	3.2	268.40 [b]	1	1
Imported feed (crude protein)	kt	1219.5	23.33 [c]	28	23
Machinery and buildings	-	-	-	10 [d]	8
Total	-	-	-	121	100

Notes: [a] Based on Statistics Denmark [20]; [b] Based on the JEC E3-database (version 31-7-2008) [23]; [c] Based on Prudêncio [24]. The energy intensity is for crude protein from soy bean and includes road transport in Brazil and shipping to Rotterdam; [d] Dalgaard *et al.* [26].

Total transport of goods related to the Danish food production system was 8.36 billion tkm per year (Table 3), which resulted in an Energy Use for transportation of 54 PJ. Foodstuff was the biggest contributor with 5.33 billion tkm per year. The transportation of agricultural products is equivalent to 39% of the total goods transport by road in tkm in Denmark counting both domestic and international transportation as well as Danish and foreign registered trucks and all types of goods. This roughly corresponds to that two of five trucks on the Danish roads served the food system and it emphasises the important role of an operational transport system in facilitating food production.

Table 3. Domestic road transport and road transport to and from Denmark of food and agricultural products in billion tonne-kilometres (tkm) and direct and indirect fossil energy use.

Products	Transport in billion tkm				Energy use [b]	
	Domestic	To DK [a]	From DK [a]	Total	(PJ)	(%)
Foodstuff	2.02	-	3.31	5.33	35	64
Animal fodder	0.71	0.08	0.17	0.96	6	12
Sugar beets, potatoes, vegetables and fruit	0.29	-	0.43	0.72	5	9
Cereal	0.41	-	0.04	0.45	3	5
Fertilisers	0.18	0.01	0.02	0.22	1	3
Live animals	0.24	-	0.19	0.43	3	5
Animal and vegetable fats and oils	0.10	-	0.15	0.26	2	3
Total	3.96	0.09	4.31	8.36	54	100

Notes: [a] For further explanation see Section 2.2.1.; [b] Based on 6.5 MJ/tkm [27].

The Energy Use for the Danish food manufacturing industry was calculated to be 69 PJ with 43 PJ coming from electricity and the rest from natural gas, oil products and coal (Table 4). Indirect energy use associated with the input of machinery and materials was not considered so the estimate of Energy Use of 69 PJ is a conservative estimate.

Table 4. Use of energy carriers in the Danish food manufacturing industry and corresponding direct and indirect fossil energy use.

Energy carriers	Input (PJ)	Energy intensity (GJ unit^{-1}) [a]	Energy use	
			(PJ)	(%)
Oil products	8.0	1.16	9	14
Natural Gas	13.5	1.13	15	22
Electricity	15.7	2.70	43	62
Coal	1.7	1.09	2	3
Total	-	-	69	100

Notes: [a] Based on the JEC E3-database (version 31-7-2008) [23].

Bioenergy is a non-food output from the Danish food production system which we considered as a negative input. The production of bioenergy was 23 PJ [35]; straw used for household heating, district heating and combined heat and power production made up 16 PJ, biogas 2 PJ and biodiesel 4 PJ. This is similar to results from 2010 [34].

In summary, the Energy Use for the entire system was combined from Tables 2–4 to be 221 PJ. If not taking credit for bioenergy into account the Energy Use was 244 PJ. This is equivalent to 28% of the gross energy consumption (fuels and renewable energy) in Denmark in 2007 (864 PJ) [35]. A large part of the indirect energy is, however, not a subset of the Danish gross energy consumption, but includes among others energy used to produce imported feed and goods.

It is notable that the Energy Use for the Danish food production system is more than 5 times larger than the input of energy carriers to the agricultural sector. This difference emphasises the importance of analysing food systems in a life cycle perspective. If the production of bioenergy (23 PJ) is compared only to the direct use of energy in the agricultural sector (43 PJ), then it seems that energy self-sufficiency for Danish agriculture is within reach and that Danish agriculture could become a net-energy producer (disregarding the lack of substitutability between the fossil energy input and the bioenergy output). Conversely, if the output of bioenergy is seen in perspective of the bigger food production system, including both indirect energy required to produce the inputs and downstream transportation and processing of the food, then the output of bioenergy is only equivalent to 11% of the fossil energy required. In this perspective the contribution from bioenergy is marginal, and it appears unrealistic to transform the food production system into a net energy producer. Even if bioenergy output was to be increased by four to seven times over the next four decades as proposed by Dalgaard *et al.* [34], the Danish food production system would still be a net-energy consumer.

3.3. Food Energy Production

In the studied period, 2004–2007, Danish livestock production was dominated by more than 20 million slaughtered pigs per year and more than 0.5 million milk producing cows. At least 69% of the agricultural area of 2,668,000 ha was used to grow animal feed (area used for grass and green fodder and fodder beets plus part of the area used for cereal and oilseed rape). Another 6% was fallow land and at least 5% of the agricultural land was used for production of non-food products such as seeds and non-food oilseed rape. Accordingly, a maximum of 20% of the agricultural area was available to produce food for direct human consumption (own calculation based on Statistics Denmark [20]).

The gross production of food for human consumption from Danish food production system was 61 PJ (Table 5), of which animal products accounted for a total of 38% (pig meat alone 15% and milk 20%). The UN recommendation for a healthy life is a daily intake of 8.8 MJ (2100 kcal) [36]. Based on this, and not taking the composition of the diet and losses of food from the farm to the consumers' stomach into account, the total yield of food was enough to provide food energy for approximately 18 million people; more than three times the Danish population of 5.5 million. However, the gross production of food should be seen in perspective of the import of feed. In the studied period, an average of 1.22 Mt crude protein or 3990 million Scandinavian feed units (1 SFU = 12 MJ of metabolisable energy, equivalent to the fodder value in 1 kg barley [26]) was imported per year. The imported feed thus translates into approximately 48 PJ of metabolisable energy, which in principle could be seen as a human food resource. Based on this, the net food-energy production (*i.e.*, gross food energy production minus import of feed measured in food energy) would thus only have been 13 PJ or the equivalent to 4.3 million people's need and not enough food for the Danish population.

Table 5. Gross annual production of food in weight and food energy.

Food types	Output (10^6 kg)	Food energy per kg (MJ kg^{-1}) [a]	Food energy	
			(PJ)	(%)
Meat, pig	1989 [b]	4.45	9	14
Meat, beef and veal	148 [b]	4.87	1	1
Meat, poultry	201 [b]	5.36	1	2
Milk	4473	2.66	12	19
Eggs	69	6.52	0	1
Cereal	1814	14.73	27	44
Sugar	425	16.98	7	12
Potatoes	1137	3.55	4	7
Vegetables and fruits	275	1.03 [c]	0	0
Total	-	-	61	100

Notes: [a] For further explanation see section 2.2.2.; [b] Slaughtered weight including meat and bone. [c] Weighted average for the 13 most commonly produced types of vegetables and fruits.

3.4. Food-EROI

For each J of fossil fuel that was invested directly and indirectly in agriculture, food manufacturing and transportation, 0.25 J of food energy was returned; 0.28 J when giving credit for bioenergy (Table 6).

In the previous study of Danish food production, the output in 1990 was estimated to be 61 PJ, and the Energy Use in the agricultural sector (without imported feed) was also estimated to 61 PJ ([17], Table 6). The latter is 2/3 of our estimate of 93 PJ (Table 6). Most of the difference is due to an almost three times higher input of electricity and two times higher input of oil products in our study. Besides a historical development in the sector, differences in system boundaries may also have contributed to the difference, e.g., it is unclear whether horticultural and greenhouse production as well as oil used for heating were included by Schroll [17].

Table 6. Direct and indirect fossil energy use and Food-EROI for accumulated compartments of the Danish food production system and Food-EROI for comparable studies.

System boundaries	Energy use (PJ)	Food-EROI		
		DK 2004–2007 [a]	**US 1995** [b]	**DK 1990** [c]
Agriculture—without imported feed	93	0.66	0.64	1.00
+ imported feed	121	0.51	0.64	-
++ Food manufacturing industry	190	0.32	0.36	-
+++ Transportation	244	0.25	0.27	-
− Credit for bioenergy	221	0.28	-	-

Notes: [a] Output 61 PJ, this study; [b] Output 1477 PJ, Heller and Keoleian [19]; [c] Output 61 PJ, Schroll [17].

The recent study of Food-EROI in US and Canada found a value larger than 2 during the last two decades when measured at the farm-gate [18]. This suggests that North America is significantly more efficient than Denmark in converting fuel to food. However, their Food-EROI is different from the study of the situation in 1995 by Heller and Keoleian [19]. The energy requirements for both studies are of the same order, but the food energy produced is assessed to be almost three times bigger by Hamilton *et al.* [18]. The analysis of the US food system in 1995 [19] shows similar Food-EROI values as our study when including manufacturing and transportation (Table 6). They also assessed energy use for packaging materials, food retail, commercial food services and household storage and preparation (not included in Table 6 or in this study) and found that these added almost 100% to the energy cost per consumed joule of food. These types of food related energy use were not included in our study due to the problems of relating energy use in households with food produced in Denmark. These problems of establishing rigorous system boundaries are especially pronounced for countries with a high degree of export and import of food such as Denmark. Overall, the results of these four studies support each other's analysis of patterns of energy consumption and material flow in the industrialised food production sector. The same kind of pattern is expected to be reflected in many industrialised countries taking part in the global market.

3.5. Limitations of the Study

A general limitation of this kind of energy analysis, where the final result is given as one number, is that the different qualities of input energy and produced food were not represented. Thus, in the calculation of the produced food, animal products rich on protein were considered equal to cereals rich on starch, and in the calculation of the indirect energy use there was no distinction between fossil energy of different qualities, *i.e.*, oil, coal and natural gas.

Another limitation is that the data on transportation were rather uncertain regarding both the quantity of tkm and the energy use per tkm. For this reason the Energy Use for transport should be considered a qualified, but rough estimate.

Finally, an unknown share of the input to agricultural production is used to produce non-food products such as fur, industry seed and seed for export. Because these inputs but not the outputs were included in the analysis, the Energy Use for production of food in the agricultural sector was slightly overestimated. However, this was not expected to make a big difference: The size of the fur production was less than 10% of the total animal production when measured in revenue; and the total area used for industry seed (mainly oilseed rape) and seed for sowing was 10% of total cultivated area. A large part of the produced seed was used in Denmark for feed or sowing and a smaller, but unknown part was used for export, non-food or non-feed.

All together these uncertainties do not change the overall picture of the structural dependency on fossil fuels in the Danish food production system.

3.6. Implication of Results

Science and technological development have given the food system in industrialised countries like Denmark and US the possibility to reach a tremendous capacity in producing food. However, most of these advances have been supported by fossil fuel and conventional energy demanding fertiliser [3]. Therefore, the ability to sustain or increase this productivity is tightly dependent on future availability of energy. The Food-EROI indicator is a useful measure of the food system's vulnerability to fossil energy constraints. Setting strategic goals for decreasing Energy Use and improving the Food-EROI can contribute to decrease vulnerability of the food production system and thus improve food security. Whether or not the quantitative results in this paper are perceived as alarming depends on how the timing and impact of Peak Oil is perceived; and this is very controversial.

Regarding the timing of Peak Oil, most developed and oil importing countries take the annual published World Energy Outlook from the International Energy Agency (IEA) into account in their long term energy and economic planning. IEA has consistently projected global oil production to increase for the time horizon of the outlook, and in 2012, the projection was 99.7 mb/d by 2035 from 87.4 mb/d in 2011 [37]. However, a growing number of researchers are questioning IEA's outlooks; see for instance [38–40]. A comprehensive review of future global oil production suggests that there is a significant risk that production will peak before 2020 [39]. The fact that global crude oil production has been more or less constant since 2005 [41] supports the latter view.

There are also opposing views regarding the impact of Peak Oil. On one side, neoclassical economists, or mainstream economists, in broad terms argue that natural capital can be substituted with human capital (see for instance [42]). In this mindset Peak Oil is not perceived as a problem because increasing oil prices will provide incentives to develop alternative energy sources once oil becomes scarce. On the other side, a growing number of biophysical/ecological economists argue that oil in particular and fossil fuel in general is a unique resource that has been a prerequisite for the explosive economic development since the industrialisation began in the 19th century (see for instance [43–48]). Furthermore, they would say that, in general terms, a decline in oil and fossil fuel production will be followed by a contraction in energy consuming activities, *i.e.*, in the global economy. This is among other due to lack of readily accessible alternative energy sources with comparable capabilities of powering an industrialised economy [49]. The global economic crisis, which has been unfolding since 2008, supports the latter viewpoint, although other factors than energy constraints have contributed also to this crisis.

Stable economic and political conditions and cheap transportation have been prerequisites for globalisation and global exchange of goods. If transport costs become too high and if economic and political turbulence lead to unstable supplies and volatile prices then the benefits of being embedded in a global supply chain will cancel out. It has been empirically shown that already volatile energy prices are leading to a reverse of globalisation [50]. As fossil oil almost alone powers the entire global transportation network and provides 33% of global primary energy consumption [51], a terminal decline of oil production is a serious, systemic threat to the global economy and global food security. This problem is enhanced by the fact that liquid fuels are predicted to be especially problematic to substitute. Large-scale produced biofuel is currently the most promising alternative to fossil fuels but its net energy level is too low [52] and labour and land demand is too high for biofuels to become a significant energy source for an industrial society [53].

If Peak Oil turns out to be both imminent and to lead to (further) contraction of global economic activity, then the risk of depending on fossil fuel and intercontinental transport to such a degree as the Danish food production system, can hardly be underestimated. For businesses, farms and governments the dilemma in relation to food security may be to choose between continuing the past trend of increasing globalisation and incremental improvements in eco-efficiency (*i.e.*, increasing output while using fewer resources [54]) or transforming the food production system to rely on local produced resources and thereby enhance resilience (*i.e.*, the capacity of the system to recover from disturbance). Even though the first option may further reduce resource consumption per unit product, it is likely to also result in reduced resilience and adaptability due to loss of diversity at all levels of the food production system. For instance, due to differences in climate and growing condition it may more eco-efficient to produce protein feed in South America and transport it to Denmark, than producing the proteins in Denmark. However, an agricultural sector that depends on import of protein feed has little tolerance against instable global economic and political conditions. In this way, investments that improve eco-efficiency may at the same time have inverse impacts on the system's resilience and adaptability [55].

An operational strategy for out-phasing fossil fuel and closing the nutrient cycle may be to increase self-sufficiency of energy, food, feed and nutrients at all spatial scales with the long term aims of (1) realigning the human population to a level that can be sustained by local and regional food production, (2) reducing livestock production to a level that can be sustained by local or regional feed production, (3) reducing usage of synthetic fertilisers and (4) developing and implementing a combination of different local renewable energy sources for agriculture and transportation (e.g., biofuels, renewable electricity, draft animals). These strategic goals do not necessarily match well with the dominating economic and agricultural paradigms but are supported by some agricultural scientists [7,56].

4. Conclusions

In this study we have shown that the Danish food production system uses 221 PJ of fossil energy (crediting for bioenergy) to produce, transport and process 61 PJ of food energy, *i.e.*, Food-EROI equals 0.28. We have also shown that the Danish food production system is based on systematic non-circular flows of feed and stock-limited fertilisers.

To avoid a dramatic decrease in food production on a global level during the next decades, oil and commercial fertiliser will need to be phased out from food production in the same pace as the rate of energy production decline. Further, the intercontinental transport of feed requires energy for transportation and leads to non-circular flows of nutrients and thus undermines the long term productivity in the donor country.

It is important to recognise that the fossil fuel dependency and non-circular flows of nutrients are systemic and structural threats. Since oil is practically all alone powering the global transportation system, there seems to be no way of having an oil-free food system that depends on the degree of transportation, which has been demonstrated in this paper. As a consequence the present system, which is highly depending on protein feed produced thousands of kilometres away, is likely to be undermined in case of future energy constraints. The task of out-phasing fossil energy will require either a giant technological leap in energy production or a fundamental reconfiguration and re-localisation of agriculture.

Conflict of Interest

The authors declare no conflict of interest.

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